

DEVELOPMENT OF THE HYBRID DOME AND RESEARCH OF ITS BEHAVIOR UNDER LOAD

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Summary. *The hybrid dome consists of a bearer frame, covered with a flexible fabric membrane. The frame comprises rigid upper beams and cable network at the bottom. Several embodiments of the dome are examined and the best one is selected. The process of pre-stressing of dome's elements is considered. The analysis of reliability of exploitation of the dome is performed.*

1 INTRODUCTION

The hybrid dome¹ to be investigated consists of a bearer frame, covered with a flexible fabric membrane. The frame comprises rigid upper beams and a cable network at the bottom, connected to the beams with hinged struts (figure 1). Rigid beams are arranged in radial direction.

The dome has several advantages in comparison to fully flexible cable structures, they are: smaller deformations and horizontal support reactions. In case of uniform external loadings bending moments in its beams are significantly lower, than in rigid structures not supported by a cable network. It allows covering large spans, not accessible to usual beams or even trusses.

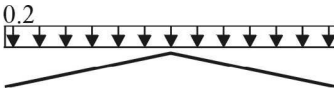
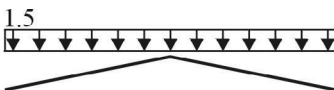
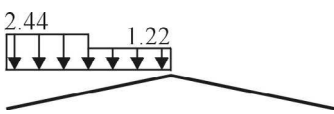
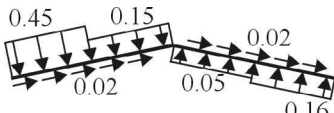
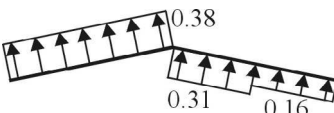
On the other hand, non-uniform loadings lead to more severe stresses in the bearer frame and may cause excessive displacements of dome's nodes. The form and topology of the bottom cable network and arrangement of the hinged struts essentially influence load-carrying behavior of the dome. The proper arrangement of cables and struts is an important task to be solved in order to achieve the best characteristics of the structure.

The research has been carried out with the help of the special computer program EASY, including the module Beam, intended for structural analysis of systems, which consist of rigid and cable elements, working together with the flexible fabric membrane.

2 EXTERNAL LOADINGS CONSIDERED IN THE RESEARCH

External loadings considered in the research are in table 1. They include self weight with pre-stressing, wind and snow loads, acting on the whole surface or a part of it.

Table 1: External loadings

Designation	Name	Area load, kN/m ²	Notes
LC0	Self weight		Load case LC0 is also added
LC1	Uniform snow		
LC2	Non-uniform snow		
LC3	Wind, variant 1		
LC4	Uniform snow and Wind of variant 1	$0.9 \cdot (LC1 + LC3)$	
LC5	Non-uniform snow and Wind of variant 1	$0.9 \cdot (LC2 + LC3)$	
LC6	Wind, variant 2		
LC7	Uniform snow and Wind of variant 2	$0.9 \cdot (LC1 + LC6)$	
LC8	Non-uniform snow and Wind of variant 2	$0.9 \cdot (LC2 + LC6)$	

Several types of the bearer frame have been examined in order to determine the most appropriate embodiment of the dome.

3 TYPES OF THE BEARER FRAMES, CONSIDERED IN THE RESEARCH

The easiest embodiment of the dome consists of flat vertical ribs, which comprise the upper beams, hinged struts and cables (figure 1). Flat ribs are connected with each other by horizontal rings. Ties 6 and 7 may be omitted.

Hybrid dome includes a number of flexible elements, which need to be tensioned in order to secure reliable behavior of the structure under different load cases. It is proposed to implement the pre-stressing of the dome by tightening bearer cables 4 and 5 (figure 1), equipped with special features, e.g. turnbuckles. The magnitude of initial tension forces in these cables has to be determined from a condition of minimization of moments in the upper beams. The flexible fabric membrane 10 also has to be tightened with cables 11 and with special features (not shown in figure 1), connecting the membrane to beams 12.

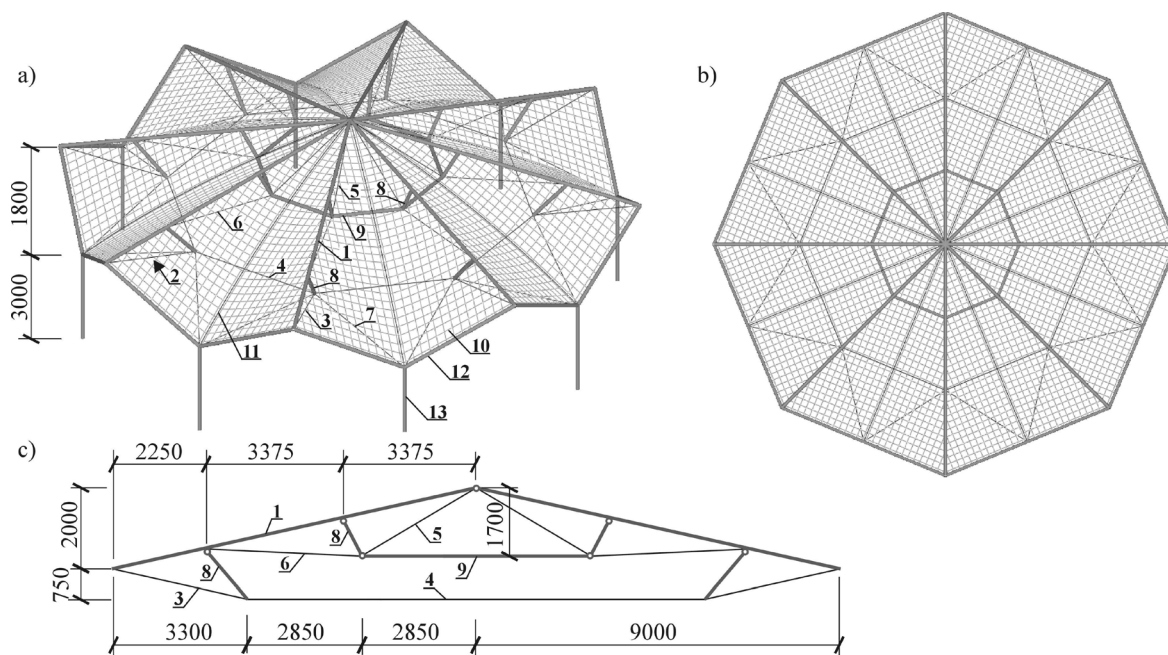


Figure 1. The hybrid dome made of flat ribs:

- a – axonometric scheme, b – top view, c – cross section; the sizes are indicated in millimeters;
 1 - upper beam; 2 - flexible network, comprising bearer cables 3, 4, 5 and additional ties 6, 7;
 8 – hinged struts; 9 – central ring, made of hinged studs; 10 - flexible fabric covering;
 11 - backstay cable for tightening the fabric; 12 – hinged beam; 13 - column

Of all load cases, considered in the research (table 1), non-uniform loadings, especially load case LC5, influence the dome in the worst manner. Bending moments in the beams of the dome partially loaded with snow, are significantly larger than moments if snow of the same magnitude acts throughout the whole surface.

In case of omission of the ties 6 and 7 excessive moments take place in the beams 1, situated between adjacent loaded and unloaded zones of the dome (so-called “out-of-plane moment”, $M_w = 15 \text{ kN}\cdot\text{m}$) and in not-loaded beams (so-called “in-plane of the rib moment”, $M_v = 31 \text{ kN}\cdot\text{m}$) - figure 2. The last one is more than 3 times larger in comparison to the moment, which occurs if the load case LC1 of table 1 is applied.

Additional ties 6 and 7 installed separately slightly influence the out-of-plane moment M_w : ties 6 reduce the moment to $13 \text{ kN}\cdot\text{m}$, while ties 7 enlarge it to $16 \text{ kN}\cdot\text{m}$. The in-plane of the rib moment M_v is more susceptible to installation of the ties. Ties 6 reduce it to $27 \text{ kN}\cdot\text{m}$, and ties 7 - to $23 \text{ kN}\cdot\text{m}$.

The most favorable effect is observed when both ties 6 and 7 are installed. The in-plane of the rib moment M_v drops to 20 kN·m, and becomes more than in 1.5 times smaller, in comparison to the omission of the ties.

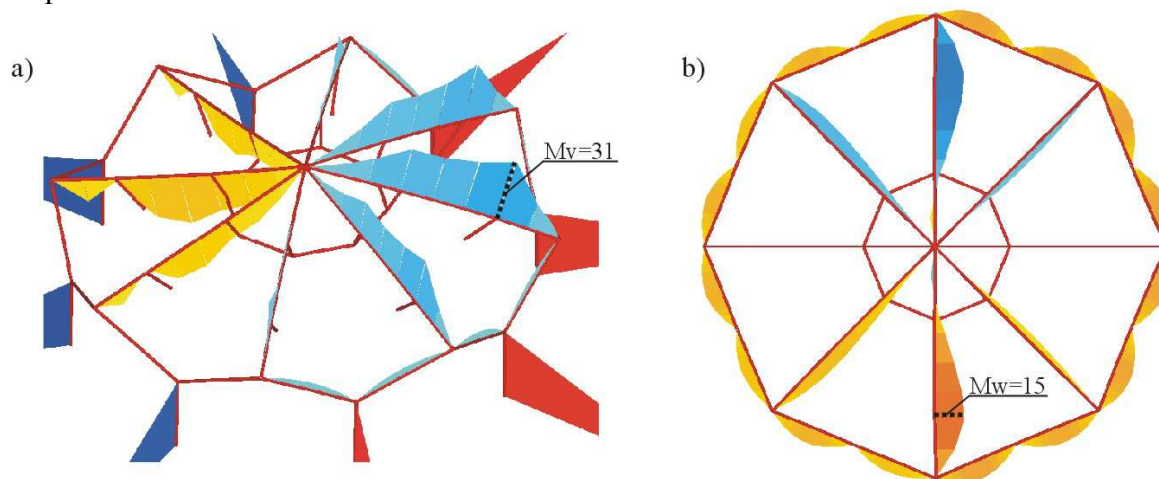


Fig. 2. Diagrams of moments (load case LC5): a – moments M_v , b – moments M_w

As so-called spatial triangulation may substantially improve load carrying behavior of the structure², vertical struts 8 of the dome were replaced with inclined struts 8a or 8b (figure 3). Addition of inclined struts in only one tier of the dome reduces the in-plane of the rib moment M_v insignificantly. On the other hand, the out-of-plane moment M_w drops almost twice up to 8 kN·m due to the emergence of a negative moment (shown with arrows in figure 3).

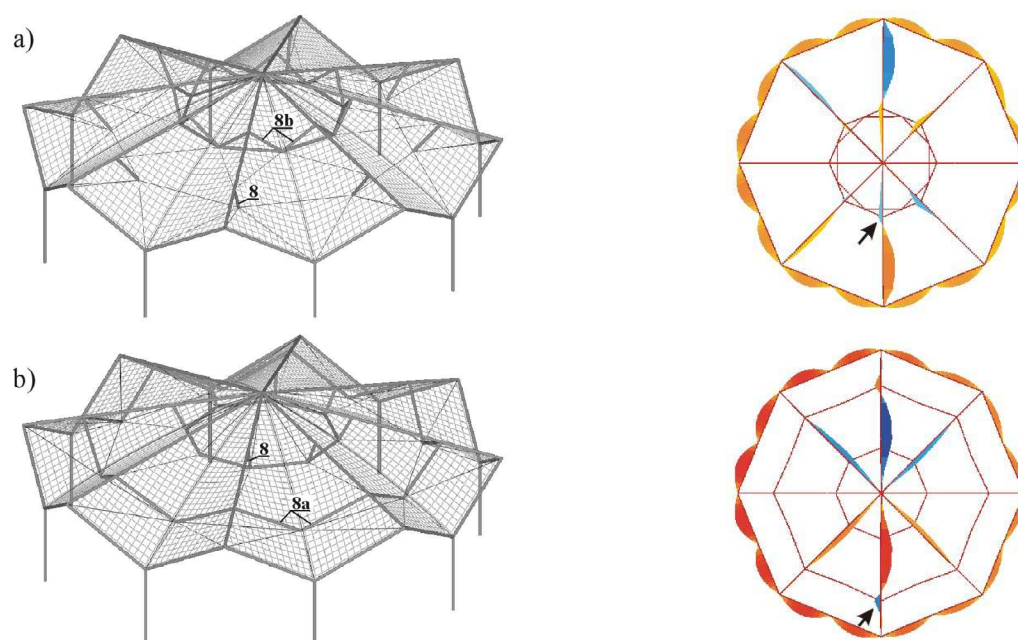


Figure 3. The hybrid dome with inclined struts in only one tier and diagrams of moments M_w :
8a, 8b – inclined hinged struts

The best results are achieved by installing inclined struts in both tiers (figure 4). Thus, the hybrid dome is assembled with a set of spatial ribs, interconnected with each other. The maximum moments in the upper beams 1 for all load cases of the table 1 are the following: $M_v = 12 \text{ kN}\cdot\text{m}$ and $M_w = 5 \text{ kN}\cdot\text{m}$.

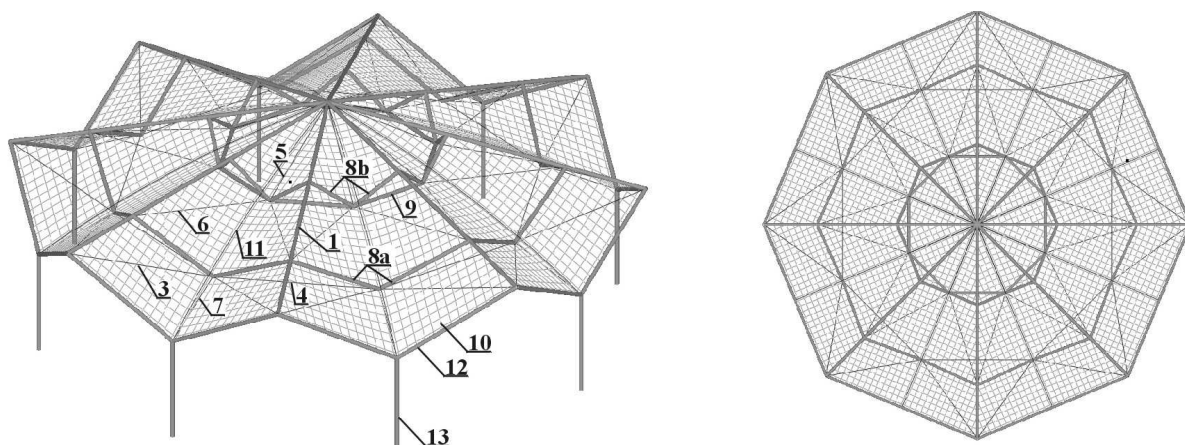


Fig. 4. The hybrid dome with inclined struts in both tiers

The tension forces in the bearer cables 4 and 5 (figure 4) required to ensure the proper pre-stressing of the dome are the following: $N_{req,4} = 84.5 \text{ kN}$ and $N_{req,5} = 21.5 \text{ kN}$.

4 PRE-STRESSING OF THE HYBRID DOME

Hybrid dome is a structure, the primary bearer frame of which, when loaded with self weight, has sufficient stability without flexible covering of a fabric membrane. Thus, hanging of the membrane has to begin after the completion of the frame³.

Before tensioning of the membrane the frame should be pre-stressed by tightening cables 4 and 5. Otherwise if the membrane is installed on the unstressed frame, loads caused by its tensioning forces together with non-uniform external effects will lead to excessive moments in the beams of the dome. These mounting moments may exceed twice the moments, caused by external loads during the exploitation of the dome.

The preliminary tension forces in the bearer cables 4 and 5 may be estimated as follows:

$$N_{pr} = N_{req} - N_{fabr} \quad (1)$$

where N_{fabr} is the force in the cable, caused by the uniform tightening of the fabric membrane only.

According to the calculations, made with the program EASY: $N_{fabr,4} = 26.5 \text{ kN}$, $N_{fabr,5} = 2.5 \text{ kN}$. Consequently, $N_{pr,4} = 84.5 - 26.5 = 58.0 \text{ kN}$ and $N_{pr,5} = 21.5 - 2.5 = 19.0 \text{ kN}$.

Before installation of the fabric membrane the moment in the upper beam of the dome influenced by the preliminary tension forces in the bearer cables 4 and 5, is equal to $11.9 \text{ kN}\cdot\text{m}$. It doesn't exceed the maximum moment in the dome covered with the membrane and influenced by external loads.

5 RESEARCH OF RELIABILITY OF EXPLOITATION OF THE HYBRID DOME

The fabric membrane, which is influenced by external adverse effects, may get damage during the long period of exploitation. The damage may initially be of very negligible dimensions, but it usually causes an emergence of overstressed zones, where the fabric is susceptible to the propagation of failure.

Let's consider a slit in the radial direction in the loaded area of the membrane, which is influenced by the load case LC5 of the table 1. Even when the slit is only 1.0 m long, the stresses in its both ends twice exceed the initial stress at the same load in the area without a slit. Under the condition, that the strength of the fabric membrane is 20 kN/m in the warp direction and 15kN/m in the weft direction (the safety coefficient 5.0 is already applied), we can trace the propagation of the failure (figure 5).

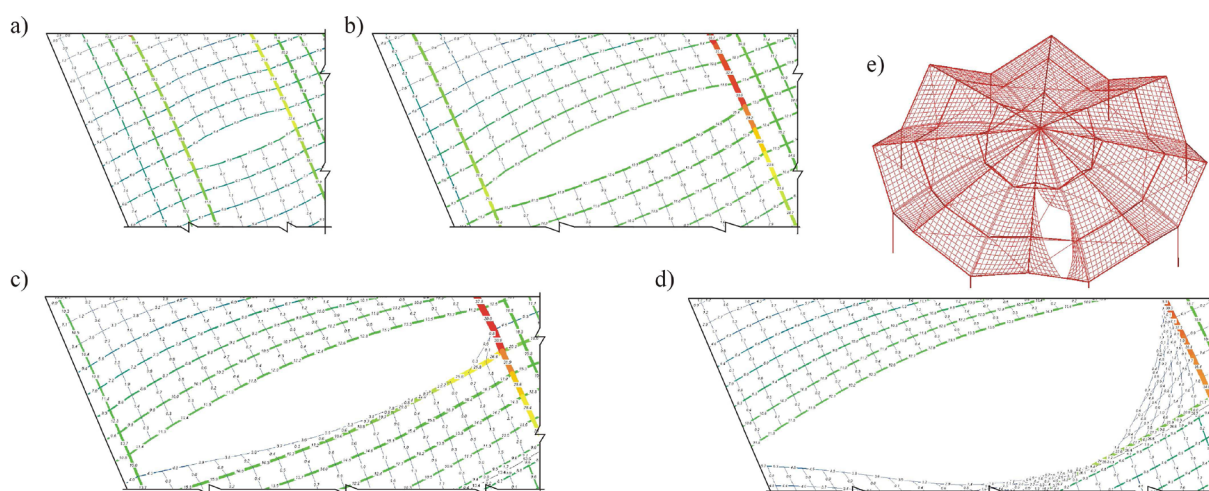


Figure 5. The propagation of the failure in the fabric membrane of the dome:
a-d are the stages of the failure; stresses in the fabric membrane are shown in kN/m;
e – general view of the dome with the failure

The figure shows that the failure, starting from a relatively small slit, propagates throughout the whole surface, confined by rigid beams. The influence of the fabric failure on the elements of the bearer frame may be estimated as follows:

$$K_T = T_i / T_0, \quad (2)$$

where T is a force N_e or a moment M_e in the corresponding element e of the dome (element numbers are on figure 4); i is the stage of the failure (figure 5); T_0 relates to the dome without a failure.

The graphs of K_T for several elements of the dome are on figure 6. Intermediate stages are added for smoothness of the curves.

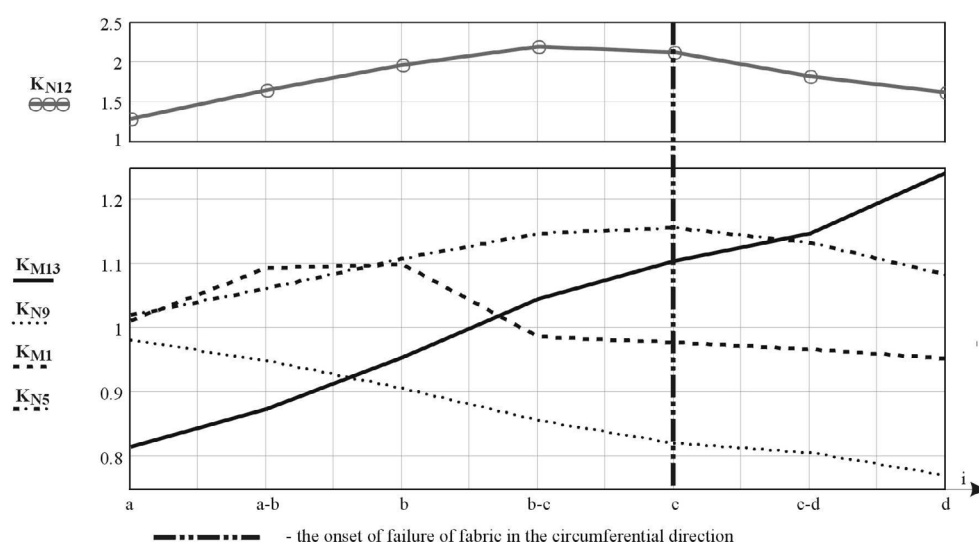


Figure 6. Illustration of the influence of fabric's failure propagation on the elements of the dome's bearer frame

The figure shows that the onset of failure of the fabric in the circumferential direction favorably influences elements of the dome (namely, the cable 5 and the beam 12), diminishing their stresses.

By neglecting this favorable effect, coefficients K_T were calculated for all elements of the dome. It was supposed that the failure of the fabric had fully propagated in the radial direction only (table 2, figure 7).

Table 2: Coefficients K_T for the last stage of failure of the fabric

Ratio	Scheme (see figure 7)						Maximum	Minimum
	a_1	a_2	a_3	b_1	b_2	b_3		
K_{M1}	0.99	1.00	1.06	1.00	1.20	1.10	1.20	0.99
K_{N3}	1.02	1.01	1.01	1.03	1.03	1.01	1.03	1.01
K_{N4}	1.01	1.01	1.03	1.01	1.03	1.04	1.04	1.01
K_{N5}	1.19	1.00	1.00	0.90	1.01	1.00	1.19	0.90
K_{N6}	1.05	1.03	0.99	1.14	1.18	1.17	1.18	0.99
K_{N7}	1.09	1.15	1.23	1.28	1.37	1.44	1.44	1.09
K_{N8a}	1.02	1.00	1.00	0.98	1.00	1.00	1.02	0.98
K_{N8b}	1.05	1.04	1.00	1.04	1.03	1.00	1.05	1.00
K_{N9}	0.76	1.00	1.00	0.63	1.01	1.00	1.01	0.63
K_{N11}	0.81	1.00	1.00	1.50	1.37	1.15	1.50	0.81
K_{M12}	2.41	1.77	1.68	1.63	1.36	1.33	2.41	1.33
K_{M13}	1.18	1.01	1.01	1.41	1.10	1.07	1.41	1.01

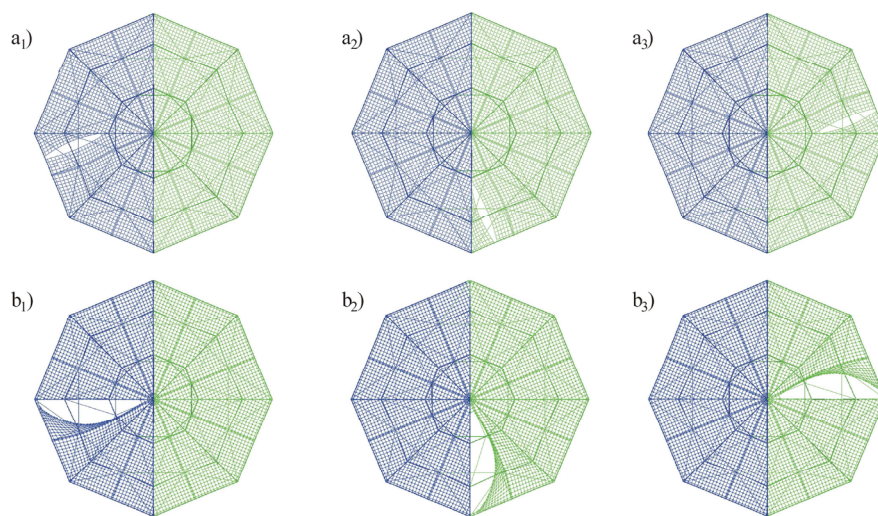


Figure 7. Schemes of damages of the fabric: the left side of each scheme is loaded with snow load, while the right side is influenced by self weight only

6 CONCLUSIONS

1. The hybrid dome which consists of the bearer frame, covered with the flexible fabric membrane is considered.
2. Several types of bearer frames have been examined in order to reduce bending moments in the rigid beams. The best results are achieved by installing inclined struts, and by forming the dome of a number of spatial ribs, interconnected with each other.
3. The cable network of the dome during mounting should be pre-stressed before the fabric covering is installed.
4. The analysis of reliability of exploitation of the hybrid dome is performed. It is established, that small damages in the fabric membrane tend to propagate throughout the whole surface, confined by rigid borders. The primary elements of the dome's bearer frame are susceptible to failure of the membrane and should be designed with the following safety coefficients: $k_s = 1.05$ for the elements 3, 4, 8a, 8b and 9; $k_s = 1.2$ for the elements 1, 5 and 6; $k_s = 1.5$ for the elements 7, 11 and 13; $k_s = 2.5$ for the elements 12. Element numbers are on figure 4.
5. The results of the work are to be used for designing and further improvement of the hybrid domes.

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